IPMC Artificial Muscles Mechatronics-Future Prospectus

M. Shahinpoor
Biomedical Engineering/Advanced Robotics
(BEAR) Laboratory
Department of Mechanical Engineering
University of Maine, Orono, ME 04469
e-mail: mohsen.shahinpoor@maine.edu

In-Space Non-Destructive Inspection Technology Workshop, Gilruth Center, NASA JSC, Feb 29 - Mar 1, 2012

There is no doubt that IPMCs are electronic nano-composites of amazing properties. Our vision of the future of IPMCs can be summarized below in terms of both medical and industrial applications. Note that IPMCs are also excellent sensors that generate huge outputs in terms of millivolts and this can be used both for sensing, transduction and harvesting energy from wind or ocean waves.

On the industrial side, due to the fact that the IPMCs are excellent sensors, energy harvesters and low-voltage actuators, they can be used for both sensing and simultaneous actuation for many engineering applications. In the energy harvesting and sensing modes they appear to have a very good bandwidth to sense low as well as high frequencies despite the piezoelectric materials such as PZT or Lithium Niobate that are only suitable for high frequency sensing.

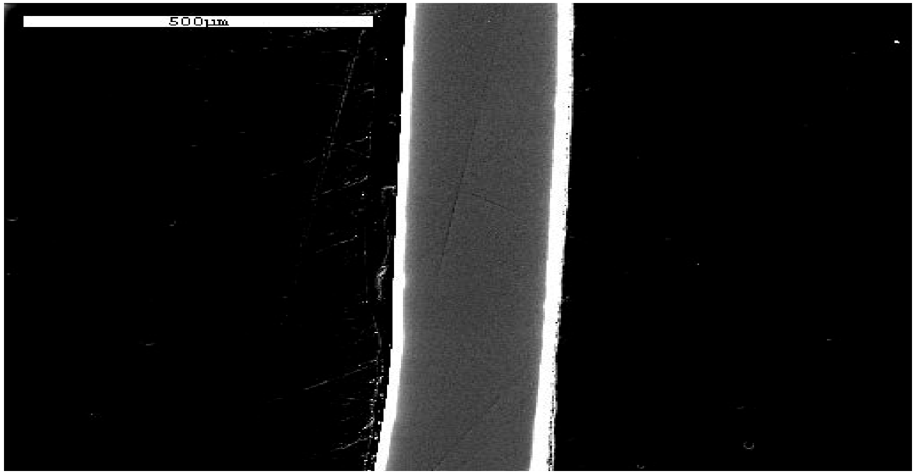
Two emerging visions of the future is to see IPMCs heavily used as a new probe in scanning probe microscopy and robotic snakes for inspection. The future of IPMC sensors and actuators for inspection applications look good (see also reference 1).

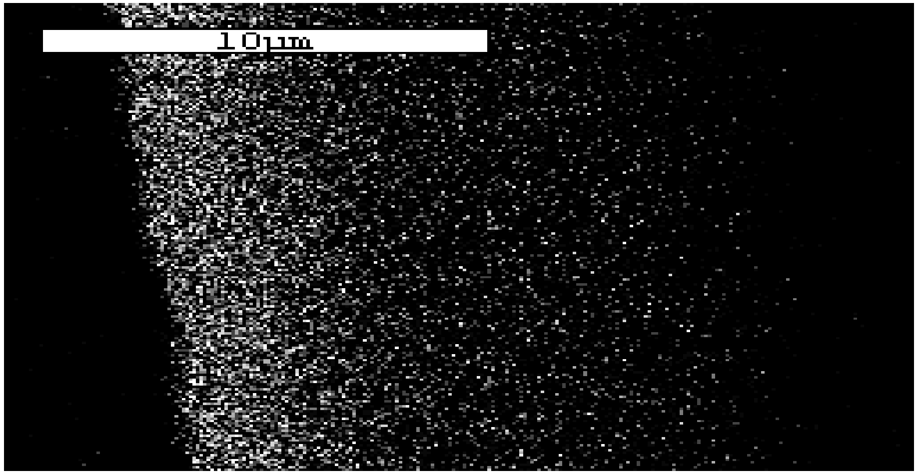
1-M. Shahinpoor and Hans-Jörg Schneider, “ Intelligent Materials”, Royal Society of Chemistry (RSC) Publishers, Science Park, Milton Road Cambridge CB4 0WF, Great Britain, 1st . Edition, (2008)

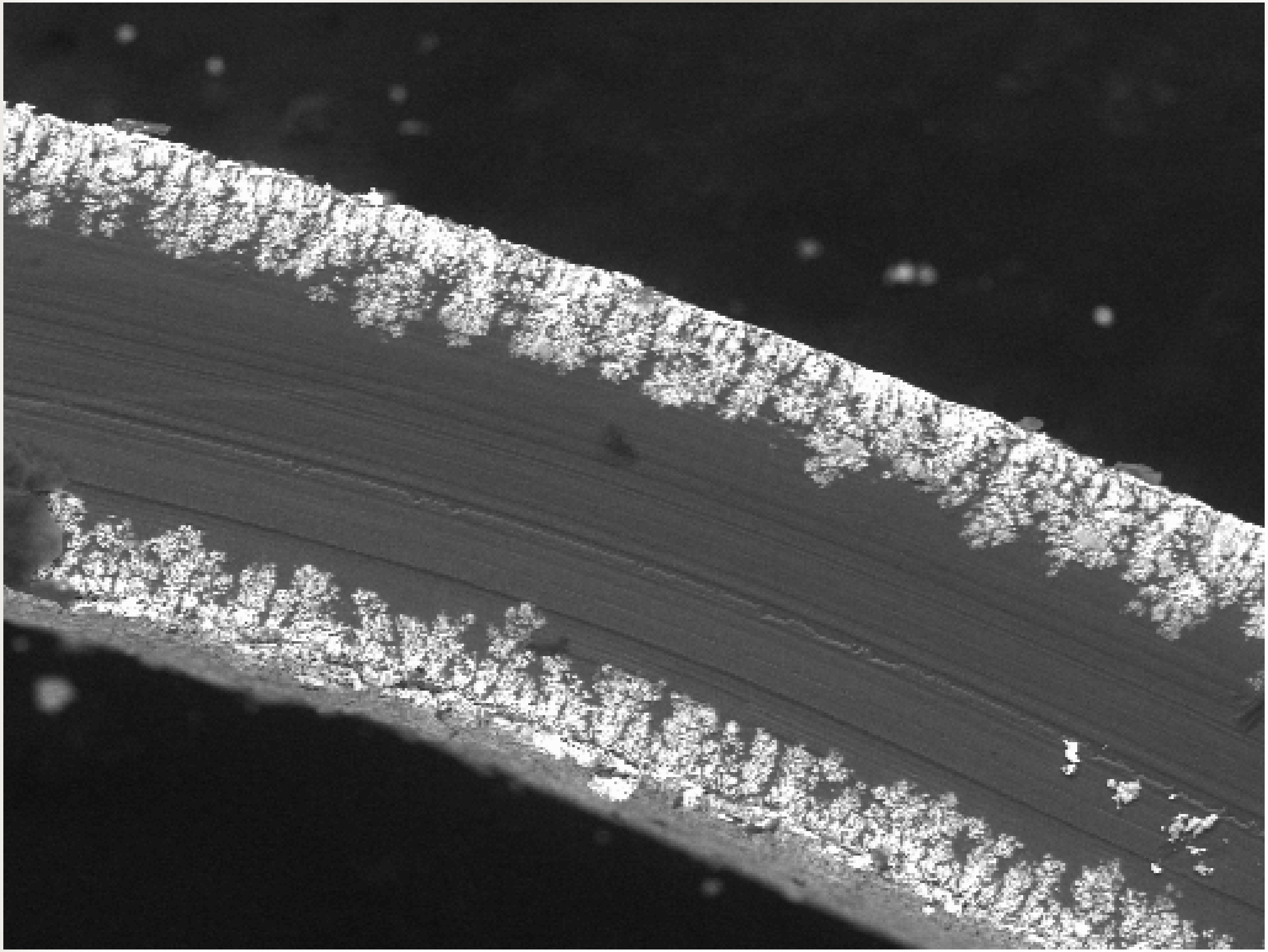
Ionic Polymer Metal Composites (IPMCs) are a family of Ionic Polymer Conductors Nano-Composite Materials (IPCNCs). The conductors may be metals, synthetic metals or conductive polymers, graphite, graphene, carbon or carbon nanotubes.

Typically IPMCs are manufactured by a REDOX chemical plating procedure in which an ionic polymer is first oxizied by a metalic salt and then reduced in a solution to allow metal nano-particles to from within the molecular network of the polymer in a fractal manner.

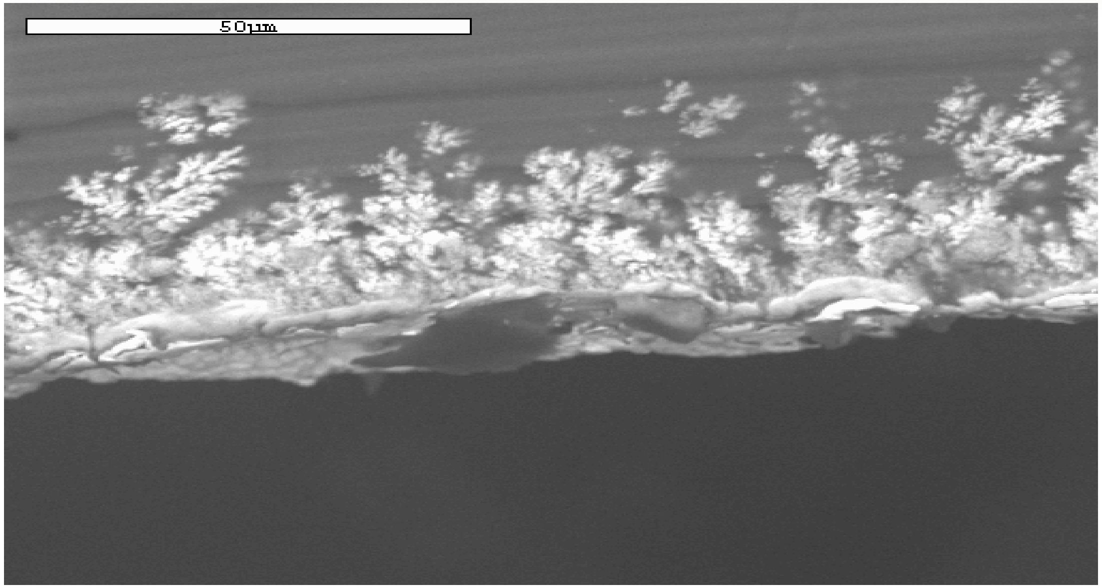
IPMC manufacturing Process

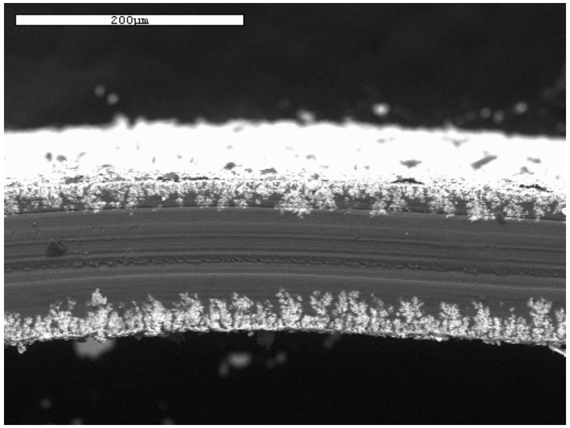


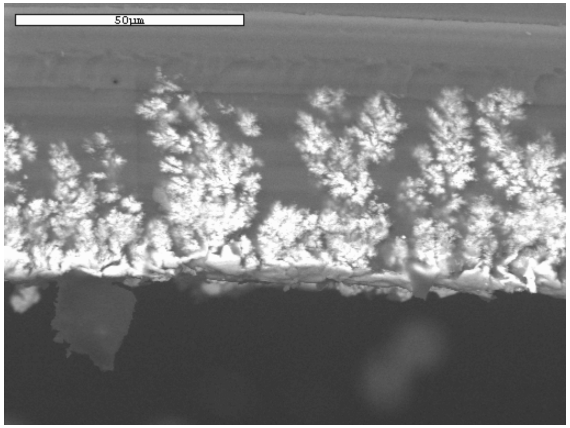




Dendritic/Fractal Penetration of Conductive Phase into Ionic Molecular Network

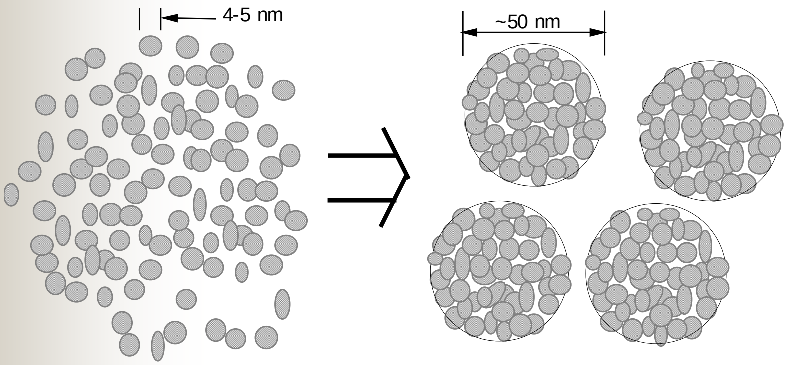


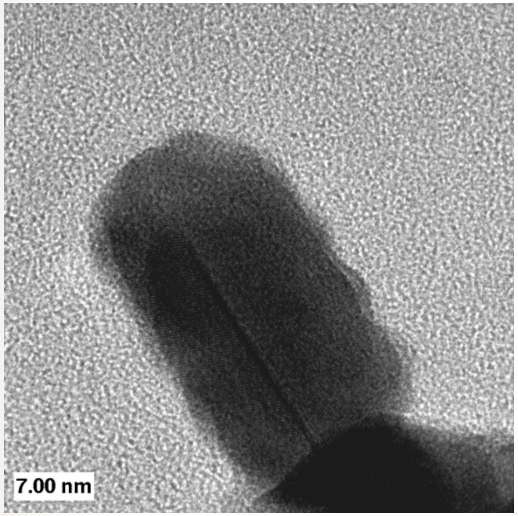


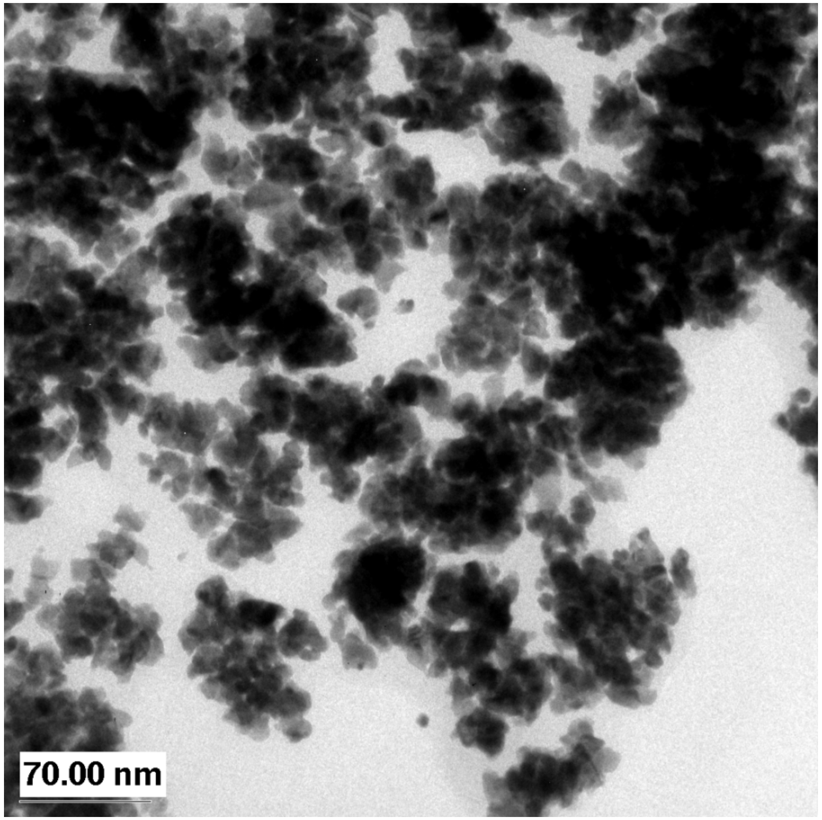


Fractal and Dendritic Penetration of Palladium Inside The Ionic Polymeric Molecular Network

Nano Particle Clusters





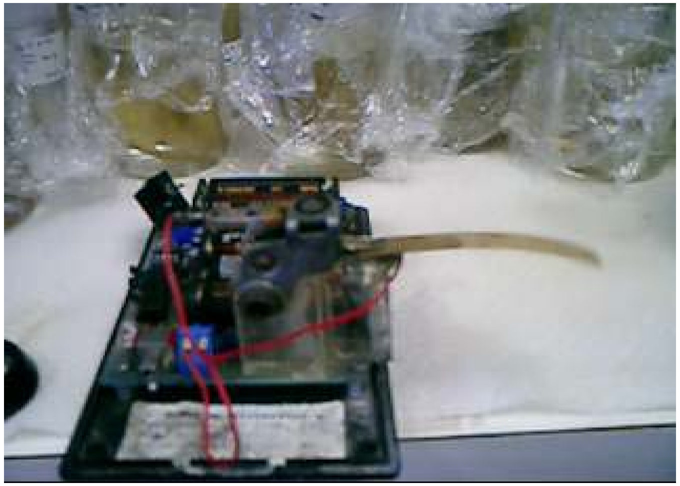


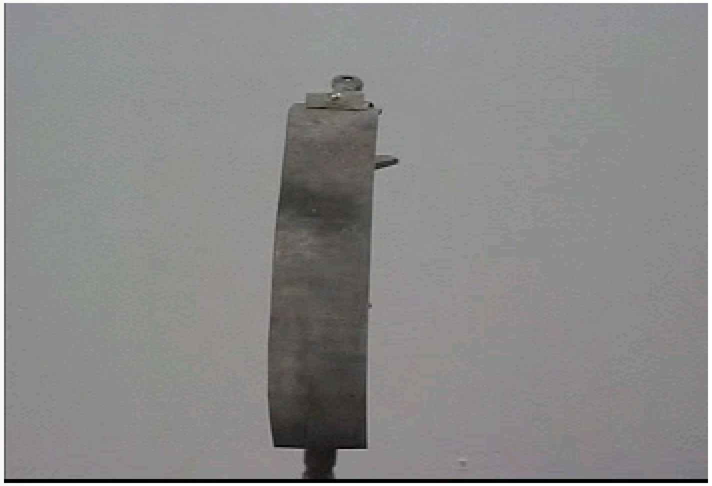
They are essentially distributed nanoacuators, nanosensors, nanotransducers, energy harvesters and Biomimetic Artificial Muscles.

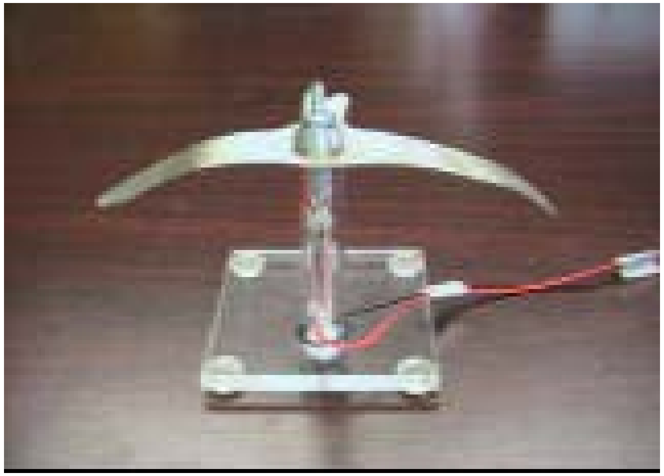
Imposition of an electric field on an IPMCs causes the conjugated ions to migrate from one region to another and redistribute and this migration and redistribution of ions induces a deformation field in IPMCs.

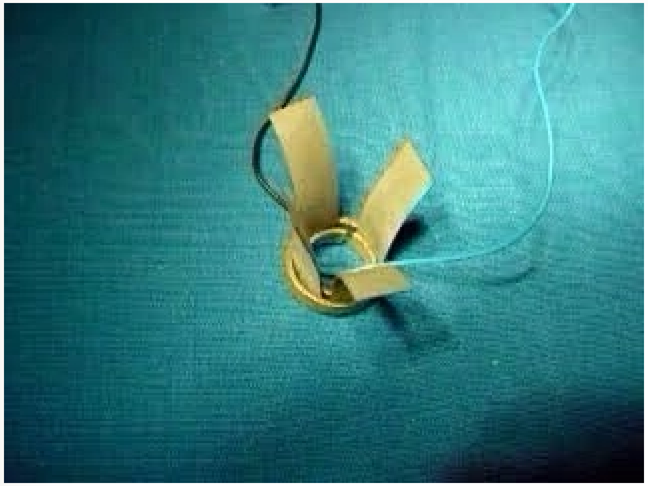
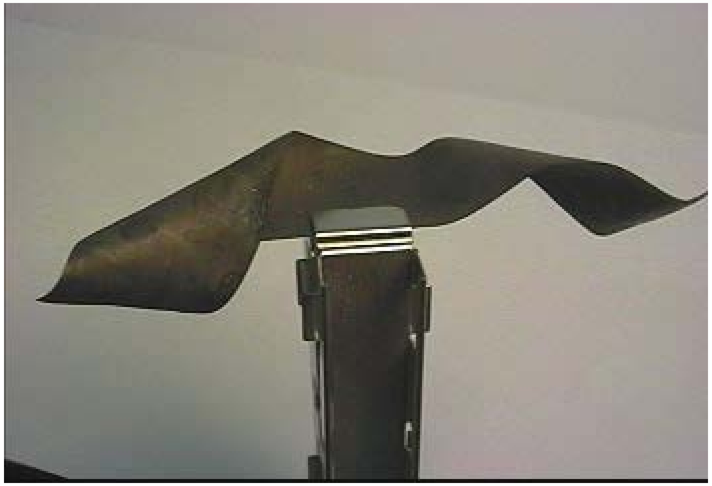
On the other hand, deforming the IPMCs will rearrange the conjugated ions and induce an electric field due to movement of ions and Poisson’s principle.

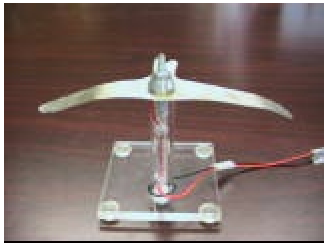
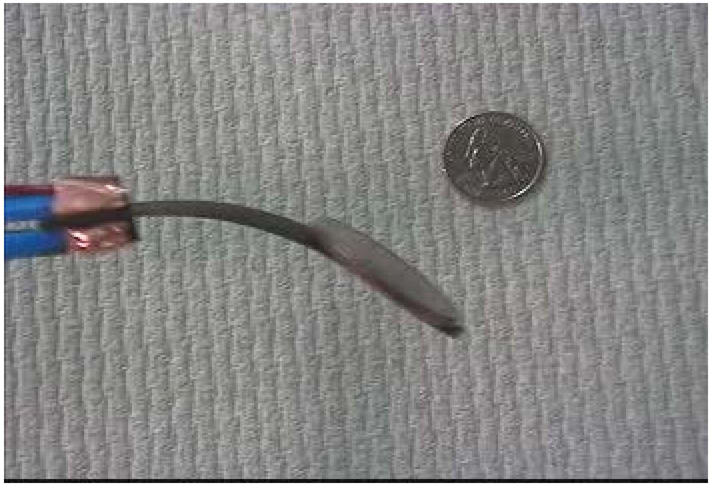
Some examples of IPMCs in action



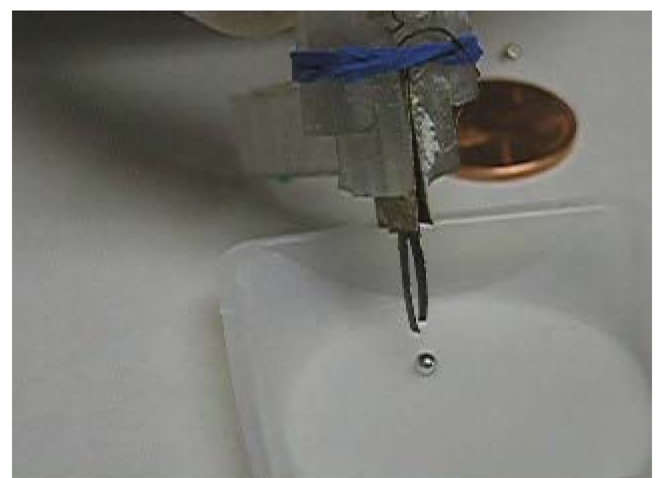


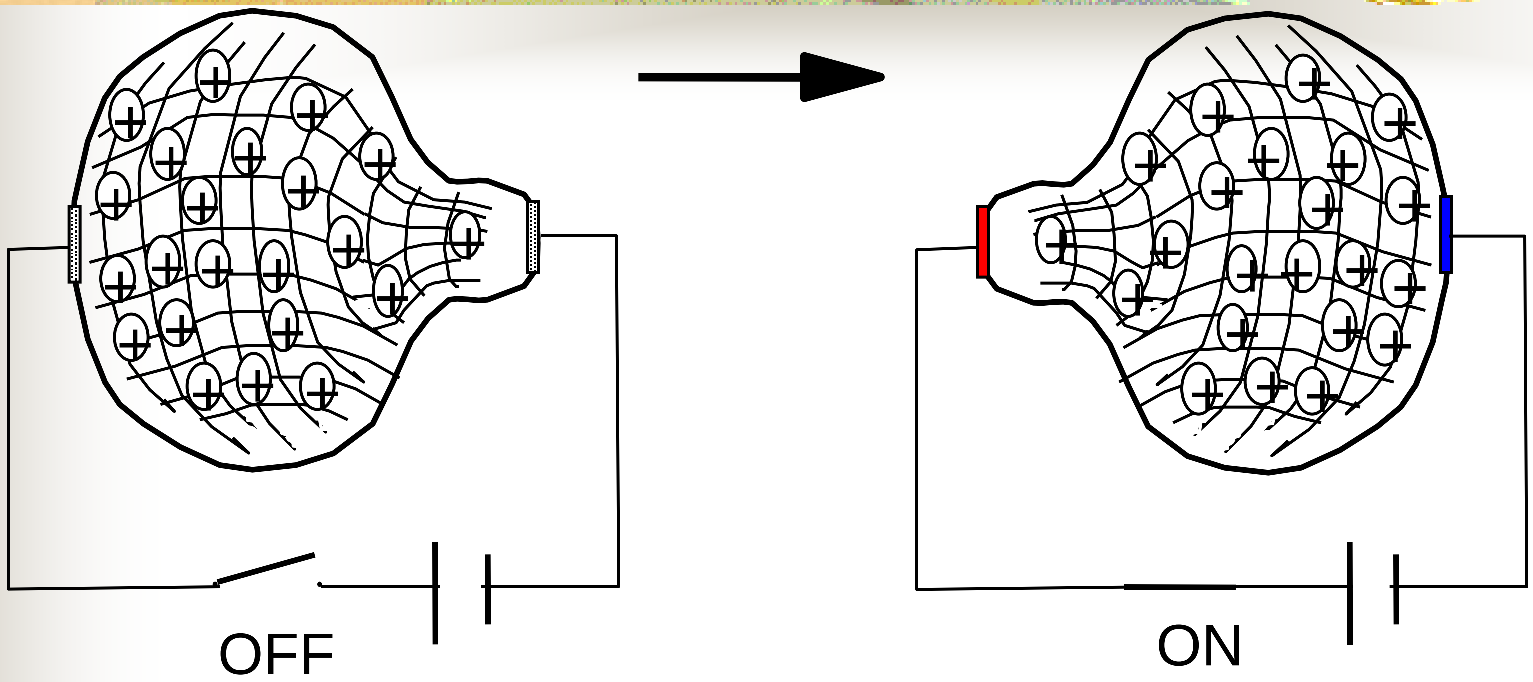


- IPMC Jelly Fish





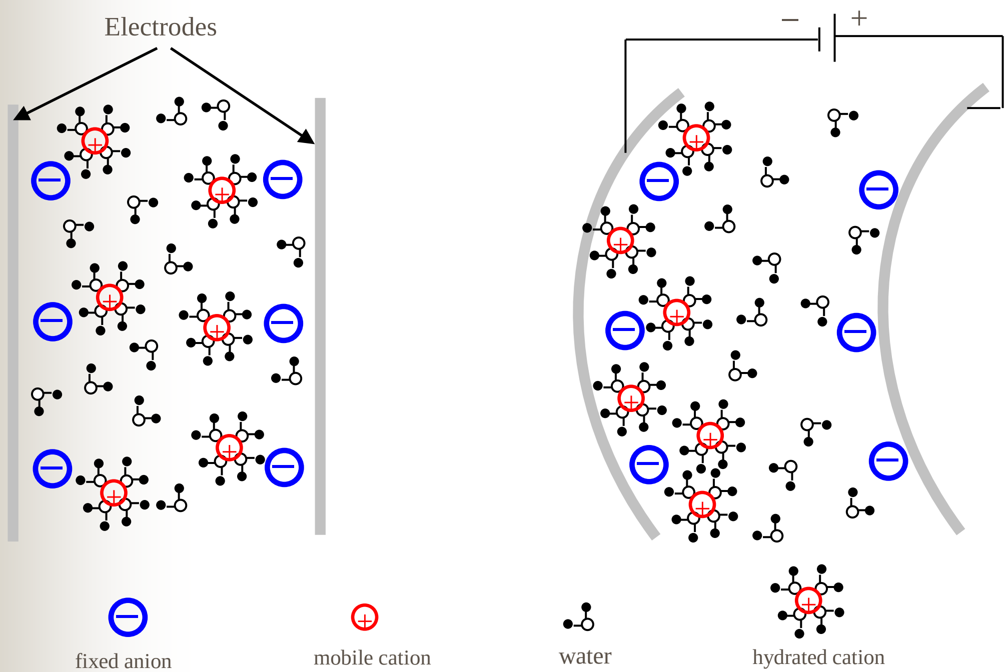
The Essence of IPMC Aritifical Muscle Technology

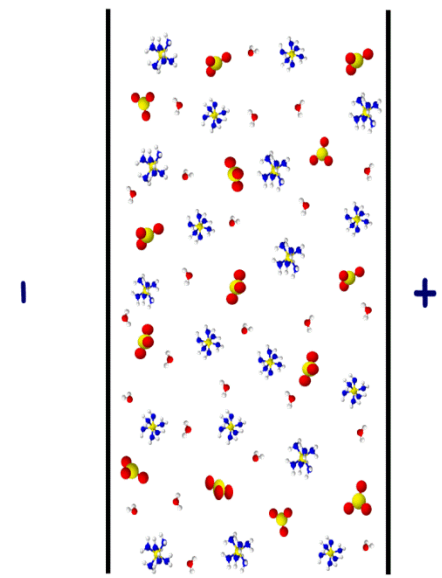
(Ion-induced Capillary Hydrodynamics)

Mechanism of Sensing and Actuation in IPMC’s:

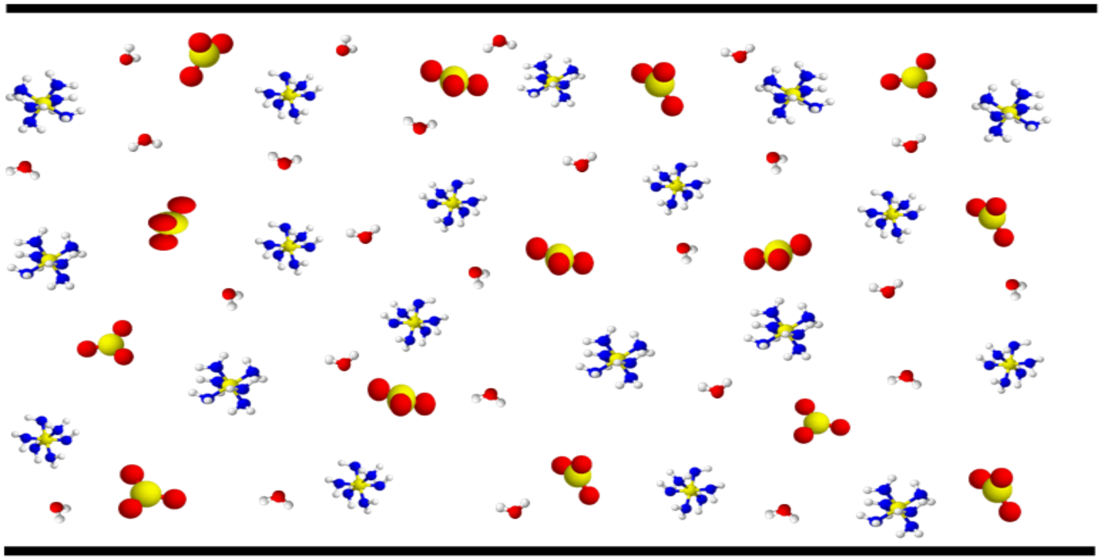
Nano-Actuation: Imposed electric field moves the cations towards the cathode thus causing bending

Nano-Sensing: Mechanical Deformation causes Cations to redistribute thus causing an streaming potential and electric field



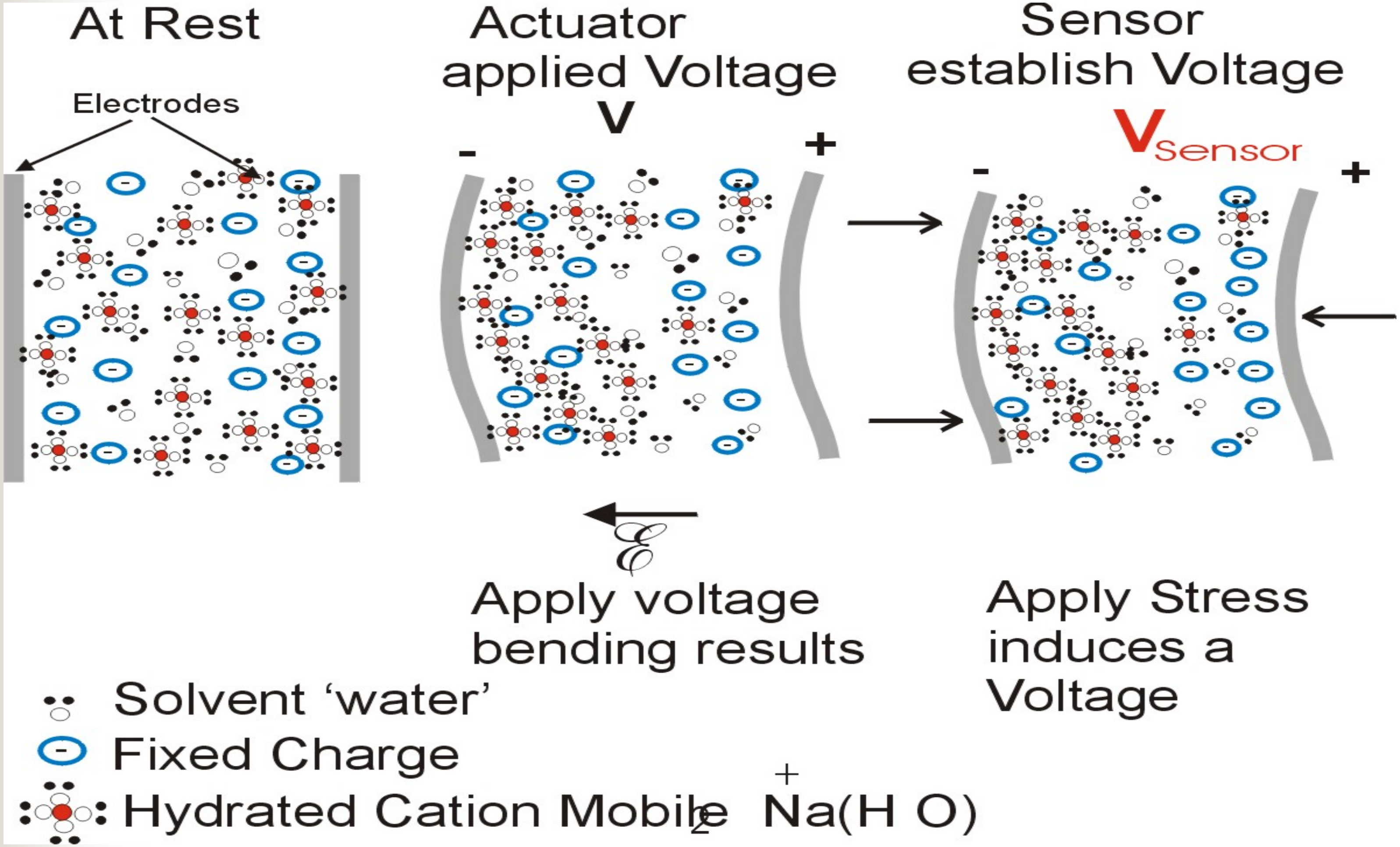


−

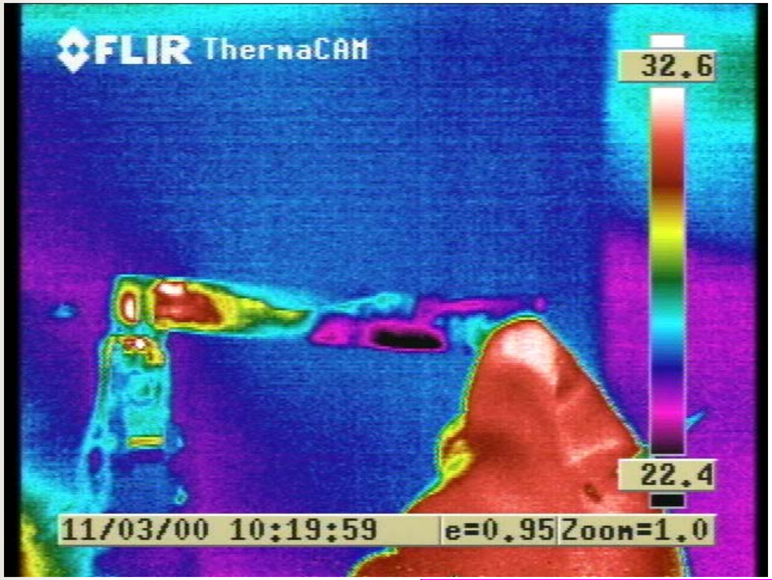


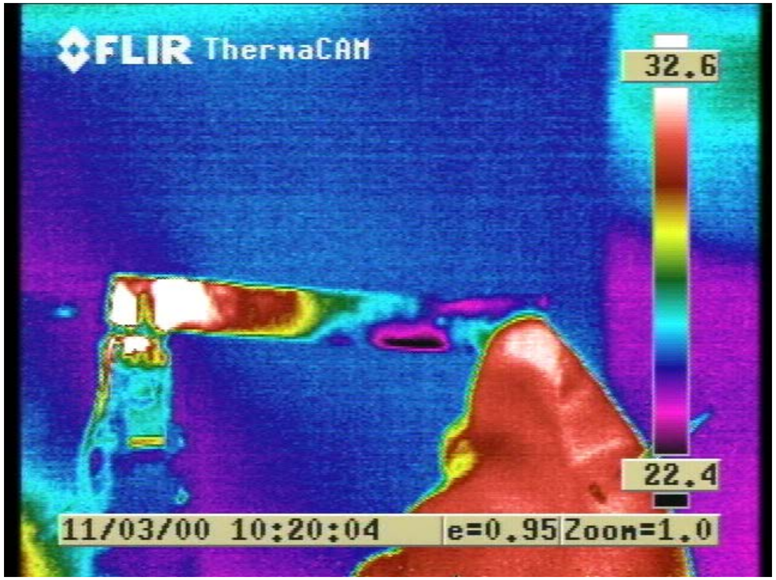
+

Typical IPMC Deformation

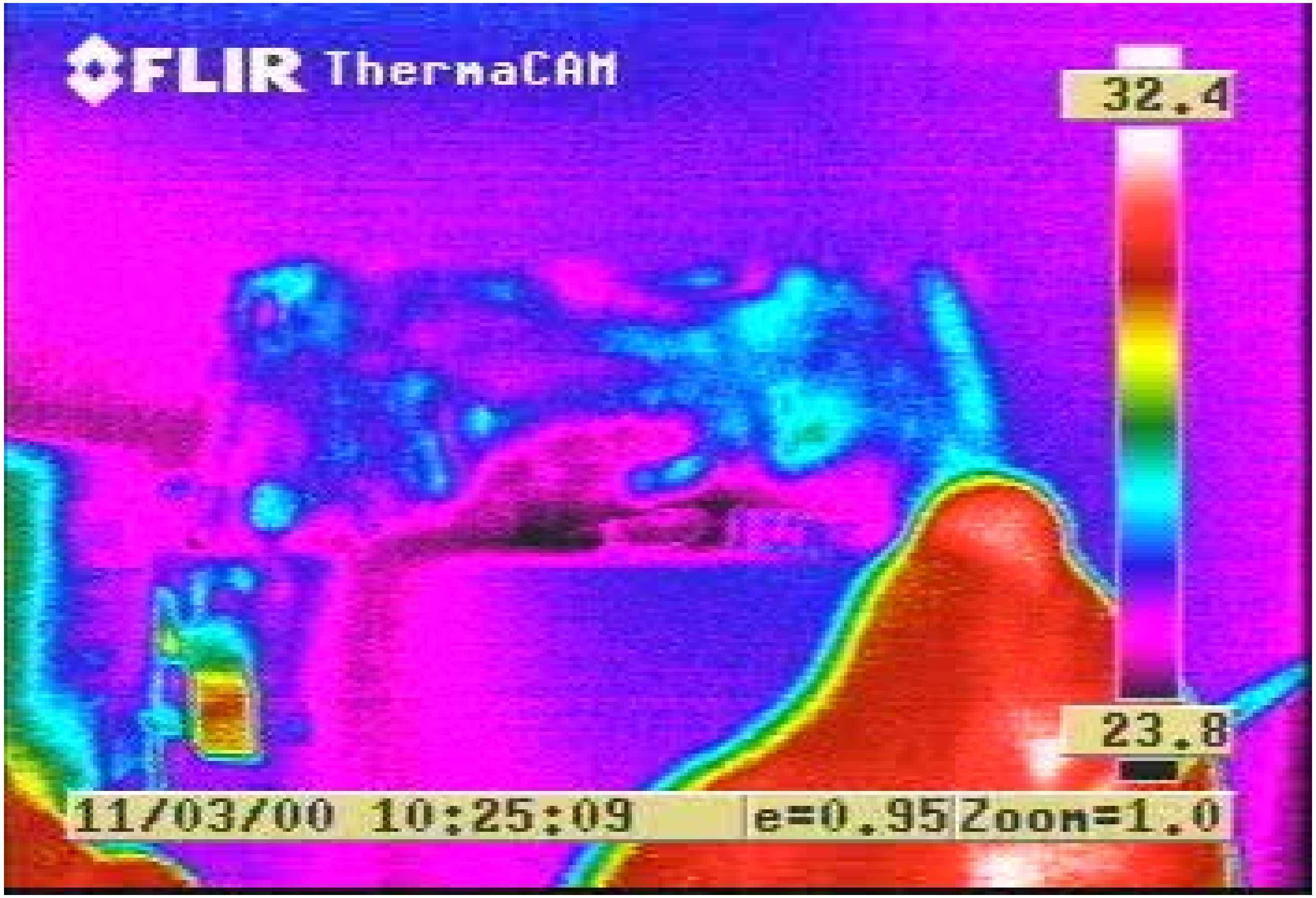


Combined Heat/Mass/Ion Transport





This complex internal migration of ions and polymeric pendant groups and clusters as well as the solvent or water transport creates an amazing dynamic infrared and thermal image:



Our Goals :

- Modelling a Multiphysics System
- Multi-hygro-thermo-electro-elasticity
- Mutliphysics PDEs
- Experimental Results
- Optimization Setup
- Report the Results in the Next BAM-NB

MODELING A MULTIPHYSICS IONIC AM SYSTEM:

The case of anisotropic multihygro-thermo-electro-elasticity 2(3+k) fields or 2(6+1+3+k) state variables

$$\left.\begin{aligned}
&\frac{\partial({}^1c)}{\partial t} = d_{c1}\nabla^2({}^1c) + d_{c2}\nabla^2({}^2c) + d_{c1}\nabla^2\theta + \gamma_{c1}\nabla^2\tau'_{kk} + h_{c1}\nabla^2 V,\\
&\frac{\partial({}^2c)}{\partial t} = d'_{c2}\nabla^2({}^1c) + d'_{c1}\nabla^2({}^2c) + d_{c2}\nabla^2\theta + \gamma_{c2}\nabla^2\tau'_{kk} + h_{c2}\nabla^2 V,
\end{aligned}\right\}\ \text{Mass Transport (2)}$$

$$\left.\frac{1-\nu}{2E}\nabla^2\tau'_{kk} + \alpha_0\nabla^2\theta + {}^1\beta_0\nabla^2({}^1c) + {}^2\beta_0\nabla^2({}^2c) + p_0\nabla^2 V = 0,\right\}\ \text{Mechanical Equilibrium (1)}$$

$$\left.\begin{aligned}
&c_T\frac{\partial\theta}{\partial t} - T_0({}^1d)\frac{\partial({}^1c)}{\partial t} - T_0({}^2d)\frac{\partial({}^2c)}{\partial t} - T_0\alpha_0\frac{\partial\tau'_{kk}}{\partial t} - T_0 g_i\frac{\partial E_i}{\partial t} =\\
&= d'_{T1}\nabla^2({}^1c) + d'_{T2}\nabla^2({}^2c) + d_T\nabla^2\theta + d'_c\nabla^2\tau'_{kk} + h_T\nabla^2 V -\\
&-\frac{1}{T_0^2}\vec{q}\vec{\nabla}\theta - \frac{1}{T_0}\sum_{k=1}^{2}\vec{J}_k\vec{\nabla}\mu_k + \frac{1}{T_0}\vec{I}\vec{\nabla}V - \frac{1}{T}\tau'_{kk}\nabla\gamma'_{kk},
\end{aligned}\right\}\ \text{Heat Conduction (1)}$$

$$\left.\varepsilon_0\nabla^2 V + p_i\gamma'_{kk,i} - g_i\theta_{,i} - {}^1h_i({}^1c_{,i}) - {}^2h_i({}^2c_{,i}) = q_c(n_- - n_+ - n_u),\right\}\ \text{Electric Displacement (1)}$$

$$\left.\vec{\nabla}\bullet\vec{I} + q_c\frac{\partial(n_- - n_+ - n_u)}{\partial t} = 0, \vec{\nabla}\bullet\vec{I}_u = -b,\ \ \vec{\nabla}\bullet\vec{I}_+ = -n_+ b,\ \ \vec{\nabla}\bullet\vec{I}_- = -n_- b,\right\}\ \text{Charge Transport (12)}$$

Total # of PDEs :: 17

MODELING A MULTIPHYSICS IONIC AM SYSTEM:

Mechanical PDEs & AEs

Phenomenological Fluxes Modification

$$q_i = -k_0 \theta_{,i} - \sum_{k=1}^{2} {}^k l_0' \, {}^k \mu_{,i} - \kappa_0' E_i - \lambda_0' \gamma_{kk,i}$$

Fourier's Law

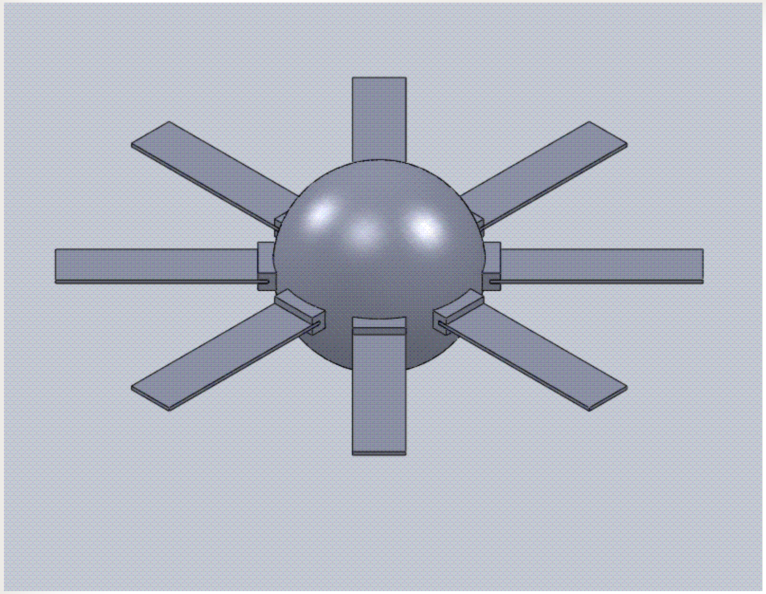
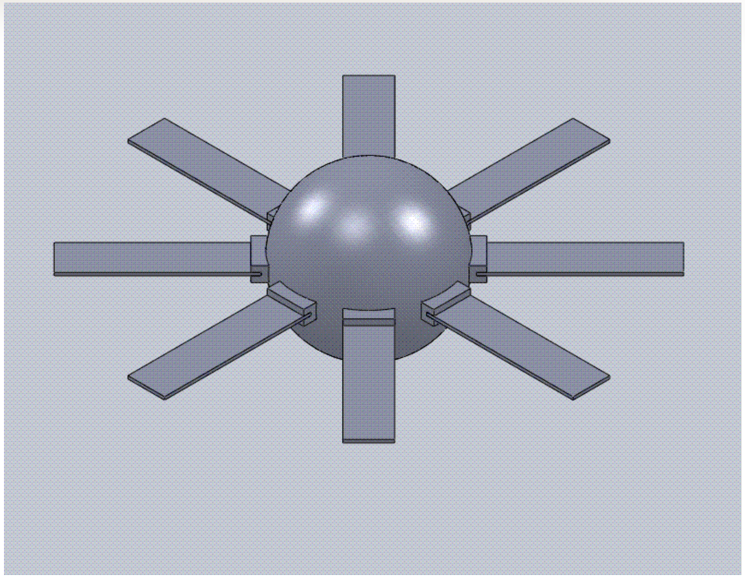
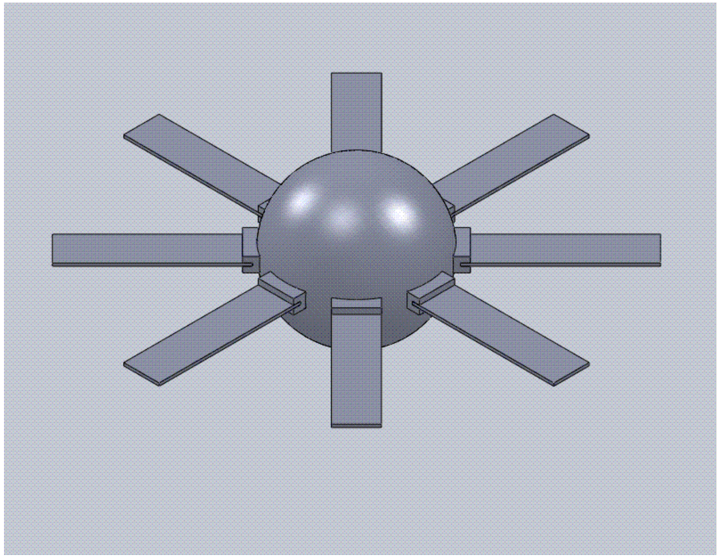
$$J_i = -k_0' \theta_{,i} - \sum_{k=1}^{2} {}^k l_0 \, {}^k \mu_{,i} - \kappa_0'' E_i - \lambda_0'' \gamma_{kk,i}$$

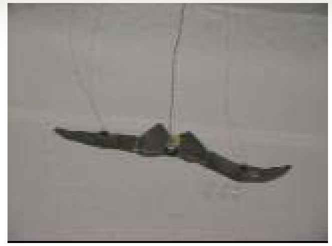
Fick's Law

$$I_i = -k_0''' \theta_{,i} - \sum_{k=1}^{2} {}^k l_0'' \, {}^k \mu_{,i} - \kappa_0 E_i - \lambda_0''' \gamma_{kk,i}$$

Ohm's Law

Implicitly, we have to deal with (6+k)x(6+k) Onsager Coefficients

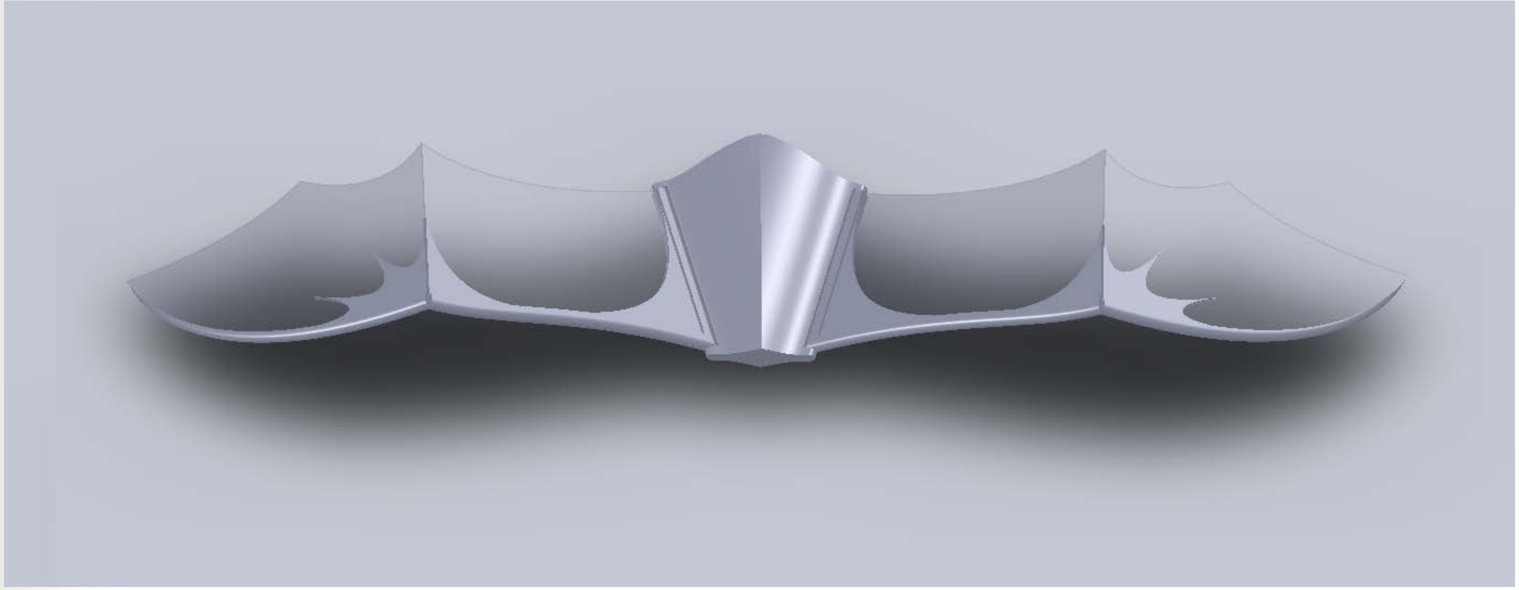




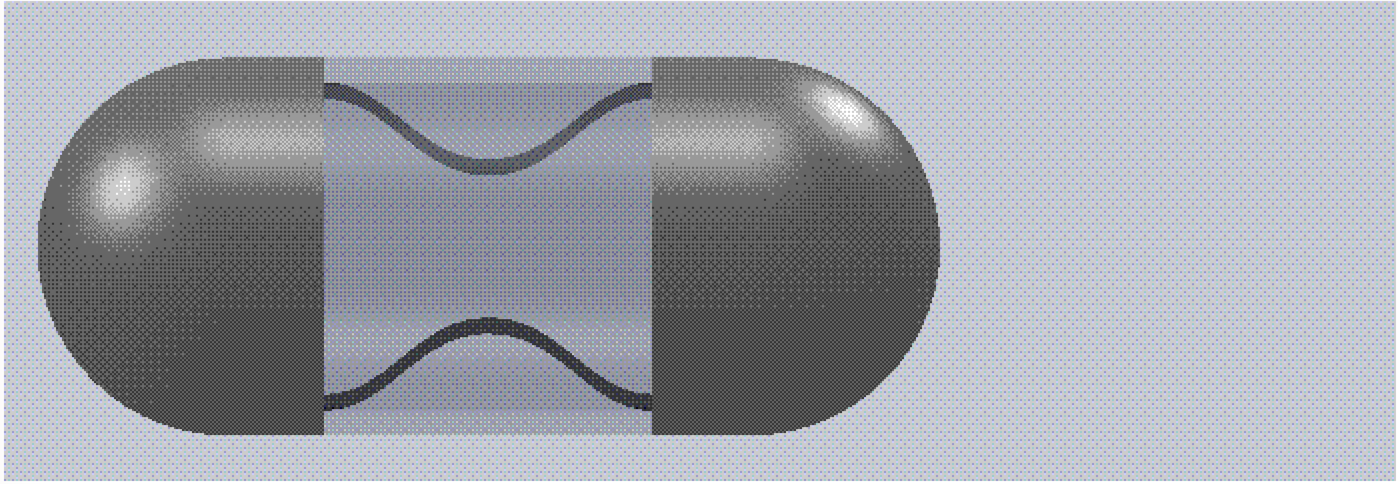


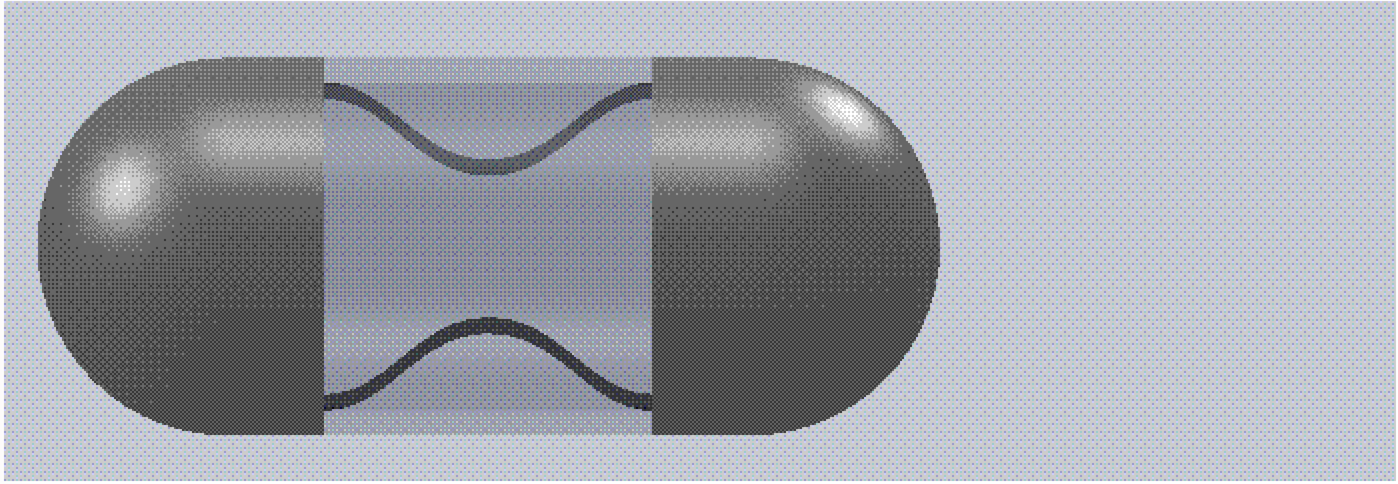




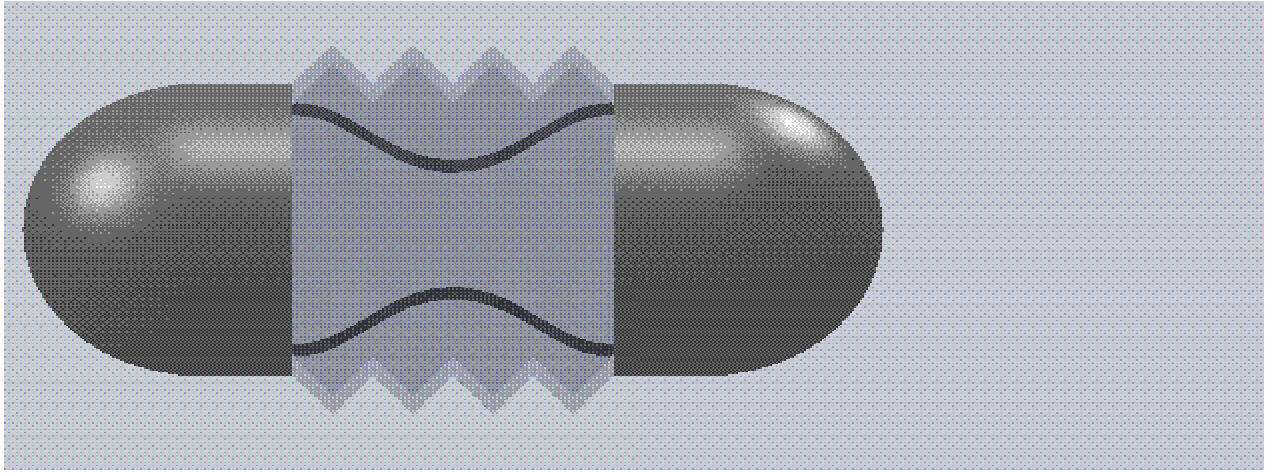



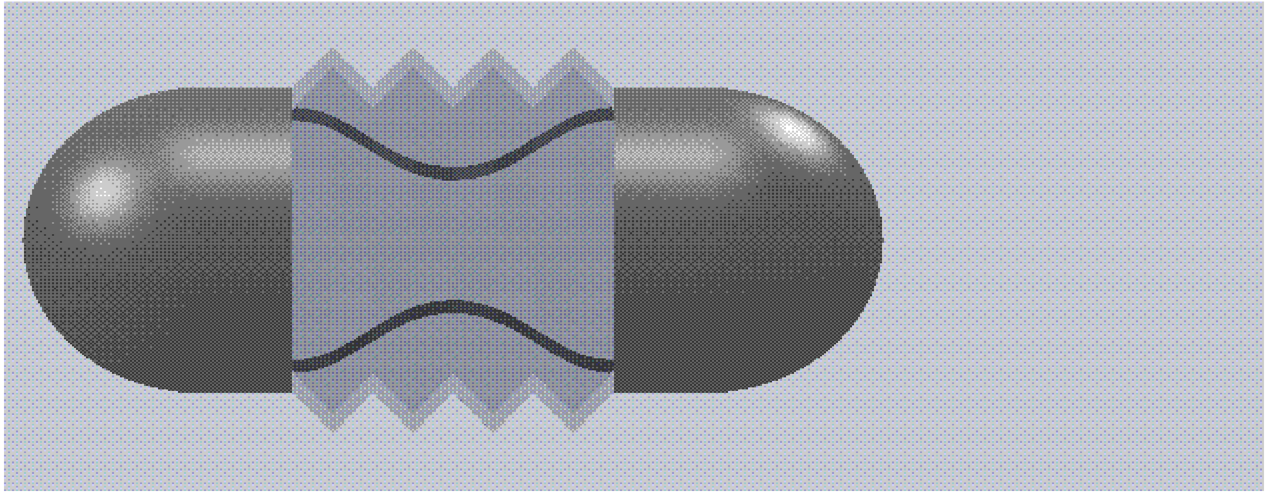
Inchworm Crawling with IPMCs-I



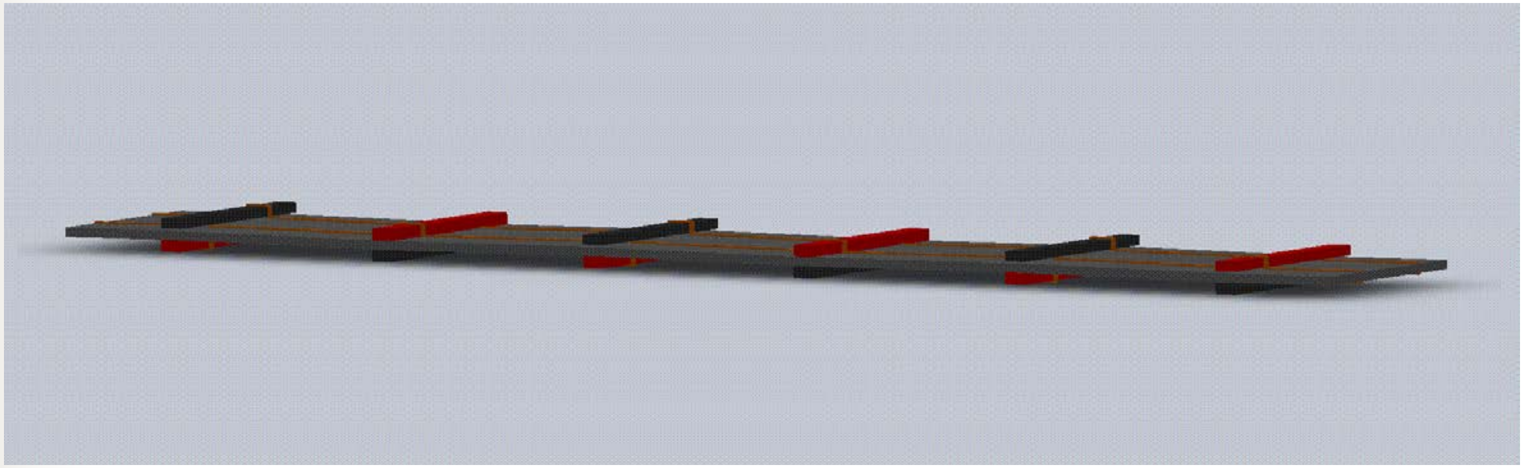


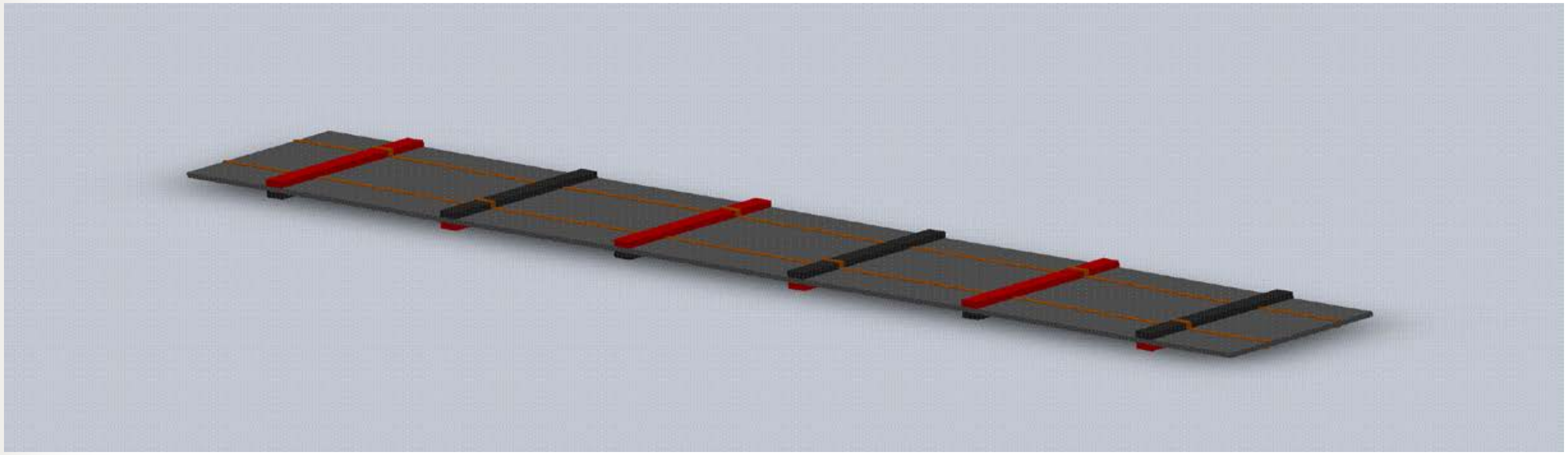
Inchworm Crawling with IPMCs-II





Inchworm Crawling with IPMCs-III





THANK YOU FOR YOUR ATTENTION

QUESTIONS?

Fundamental of IPMCs:

History of IPMC Patents :

D. Adolf, M. Shahinpoor, D. Segalman and W. Witkowski, "Electrically Controlled Ionic Polymeric Actuators“, United States Patent Number 5, 250, 167, Issued October 5, (1993), (IPMCs)

Keiskue Oguro, HiroyasuTakenaka, Youji Kawami, “Actuator element” United States Patent 5,268,082 , Issued December 7, 1993 , (IPCF)

Shahinpoor, "Spring-Loaded Ionic Polymeric Actuator,", United States Patent No. 5,389,222, Issued February 14, (1995),

M. Shahinpoor, and Mojarrad, M," Soft Actuators and Artificial Muscles", United States Patent No. 6,109, 852, issued August 29, (2000)

M. Shahinpoor and M. Mojarrad, "Ionic Polymer Sensors and Actuators", United States Patent No. 6, 475,639, Issued November 5, 2002.

M. Shahinpoor and K.J. Kim, “Method of Fabricating a Dry Electro-Active Polymeric Synthetic Muscle”, *US Patent Office*, Patent No. 7,276,090, Issued October 2, 2007